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# Canadian emissions and unconventional oil production exceed the 2°C global warming scenario

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## Highlights

- Canada extracted more unconventional oil than its budget for the entire century.
- Canadian fossil fuel industry global emissions increased by 32% from 2011 to 2019.
- Global emissions of this industry represent 2.1 times entire national emissions.
- Annual national emissions exceed targets set by three models of the 2°C scenario.
- Policies to limit exports of fossil fuels and national emissions should be implemented.

## Abstract

Canada could highly impact the climate, as it possesses the world's third largest resources of unconventional oil. This paper evaluates in three ways whether Canada is respecting a scenario of fossil fuel production and *greenhouse gas* (GHG) emissions limiting warming to 2.0 °C by 2100. Firstly, McGlade and Ekins (2015) proposed a model providing production budgets for each fossil fuel producing country. Data show that Canada has extracted more unconventional oil than allocated for the entire century. Secondly, global GHG emissions from the Canadian fossil fuel industry were computed using a life-cycle analysis. Emissions increased by 32% from 2011 to 2019, although dropping 4.9% in 2020 because of the COVID-19 pandemic. Results also show that an increase of 1% in Canadian fossil fuel industry emissions cancels out at the global level a decrease of 2.1% in national emissions. Thirdly, three models providing a national carbon budget for Canada were compared to annual emissions. Emissions were higher than the targets set by these models. In conclusion, Canadian GHG emissions and unconventional oil production exceeded the amounts allowed by the 2°C scenario during the 2011-2020 period. Policies to reduce exports of fossil fuels and mitigate national emissions are discussed.

*Keywords:*

Fossil fuels; Emissions; GHG; Canada; Warming

# 1 Introduction

Canada merits special attention concerning climate for several reasons. Canada has the third largest proven reserves of oil in the world with 169.7 billion barrels in 2019 (BP, 2020). It also has the third largest resources of unconventional oil after the US and Venezuela (IEA, 2008; Jaffe et al., 2011). Burning all Canadian fossil fuel resources would generate more *greenhouse gases* (GHG) than the *Global Carbon Budget* (GCB) that should not be exceeded in order to limit warming to 2.0 °C by 2100 (McGlade and Ekins, 2015). Finally, in 2018 Canada had the second highest level of GHG emissions per capita of the G7 after the USA. That year Canadians emitted on average 19.7 tonnes of GHG, while Americans emitted 20.4 tonnes (OECD, 2020; United Nations, 2019).

The aim of the present paper is to answer the following question: Is Canada on a path to respect a scenario of fossil fuel production and GHG emissions providing a 67% chance to limit warming to 2.0 °C by 2100? This question is addressed by dividing it into three sub-questions. The first sub-question is: Does the exploitation of fossil fuels respect the quotas proposed by McGlade and Ekins' (2015) model to limit warming to 2.0 °C? To answer it, one has to compare the cumulative Canadian production to the quotas provided by the global model proposed by these authors. Based both on economic and climate factors, they computed the proportion of coal, oil and gas that should not be burned to avoid emitting more than the upper limit of the GCB for the 2°C scenario. They provided these proportions for the major fossil fuel producing countries including Canada. These proportions can be interpreted as production quotas (or production budgets). Major environmental organizations have adopted this view, but not the Canadian government (350.org, 2016; Abel et al., 2018; Cimons and Nesbit, 2016; Green, 2019; Trudeau, 2017). No scientific publication has assessed whether or not these limits have been respected or exceeded and whether Canada respects the 2°C scenario. The present paper computes the percentage of these quotas already spent and finds that the limit for unconventional oil has been exceeded.

The second sub-question is: Are the global emissions of the Canadian fossil fuel industry decreasing? To address it, the GHG emissions of Canadian fossil fuel production is assessed by computing global emissions using a *life-cycle analysis* (LCA). As this evaluation is global, it includes GHG released by burning exported fossil fuels. Emissions excluding exported fossil fuels are examined in the following sub-question. It is important to assess LCA emissions because an increase in Canadian fossil fuel industry production could cancel out at a global level the national

efforts to decrease emissions. In brief, results below show that such emissions have increased by 32% from 2011 to 2019.

The third sub-question is: Do Canadian national emissions respect the *Carbon Budget* (CB) proposed by different models simulating the 2.0 °C scenario? To answer it, Canadian emissions were compared with the proposed emission budget of three models. Many more models have been proposed to distribute the GCB amongst nations. However, only three models were identified that published explicit predictions about the CB of Canada (Alcaraz et al., 2018; Gignac and Matthews, 2015; Kanitkar et al., 2013). These are the models examined below and the results demonstrate that Canadian national emissions exceed the annual budget according to each of the three models presented. Several policies are discussed to limit exports of fossil fuels and to mitigate national emissions.

## **2 Canadian “unburnable” fossil fuels**

### **2.1 McGlade and Ekins’ (2015) Model**

The concepts of ‘resources’ and ‘reserves’ of fossil fuels are distinct. McGlade and Ekins (2015) define resources as the *Remaining Ultimately Recoverable Resources* (RURR) - the quantity of fossil fuels “that is recoverable over all time, with both current and future technology, irrespective of current economic conditions.” Reserves are a subset of resources that are “recoverable under current economic conditions and have a specific probability of being produced”.

McGlade and Ekins (2015) computed the proportion of coal, oil and gas resources that should not be burned to avoid emitting more than the upper limit of GCB for the 2°C scenario. They estimated that combustion of all world fossil fuel reserves would generate about 2,900 *Gigatonnes of carbon dioxide* (GtCO<sub>2</sub>) and 11,000 GtCO<sub>2</sub> for all fossil fuel resources. This evaluation was based on multiple sources (Attanasi and Freeman, 2011; Babies et al., 2012; Iancu et al., 2010; IEA, 2013, 2011, 2008; Rogner et al., 2012). As this is much higher than the GCB, a significant proportion of these fossil fuels should stay in the ground. To determine production until 2050, they used their TIAM-UCL model (Anandaraja et al., 2011), a whole-system model maximizing social welfare under constraints, in conjunction with the climate model MAGICC (Meinshausen et al., 2011).

McGlade and Ekins found that globally 33% of oil, 49% of gas and 82% of coal should stay in the ground, and proposed quotas for each producing country. They concluded that Canada should leave in the ground 98% of hard coal, 97% of lignite, 72% of conventional oil, 99% of unconventional oil, 73% of conventional gas and 71% of unconventional gas (see Table 1). Note that the last three columns about GHG in Table 1 are original to the present paper and will be discussed in Section 3 below.

**Table 1**

Amount of Canadian fossil fuel resources to leave in the ground or to exploit according to the 2°C scenario

	Amount to Leave <sup>a</sup>	Amount to Exploit	Total Resources (RURR) <sup>a</sup>	Units	% to Leave in the Ground <sup>a</sup>	% to exploit	CO <sub>2</sub> e to Leave (Gt)	CO <sub>2</sub> e to Emit (Gt)	Total CO <sub>2</sub> (Gt)
<b>Hard Coal</b>	34.3	0.7	35	Gt	98.0	2.0	85.3	1.7	87.0
<b>Lignite</b>	38.8	1.2	40	Gt	97.0	3.0	57.1	1.8	58.9
<b>Conventional Oil</b>	43.2	16.8	60	Gb	72.0	28.0	20.3	7.9	28.2
<b>Unconventional Oil</b>	632.5	7.5	640	Gb	98.8	1.2	429.6	5.1	434.7
<b>Conventional Gas</b>	3.6	1.4	5	Tcm	72.5	27.5	8.9	3.4	12.3
<b>Unconventional Gas</b>	17.8	7.3	25	Tcm	71.0	29.0	43.5	17.8	61.3
<b>Total</b>							644.7	37.6	682.4

RURR = Remaining Ultimately Recoverable Resources, Gt = gigatonne, Gb = gigabarrel, Tcm = trillion cubic meters, CO<sub>2</sub>e = CO<sub>2</sub>-equivalent.

<sup>a</sup>Source: McGlade and Ekins (2015).

## 2.2 Methods

All raw data and detailed calculations for this section and the next ones can be downloaded from the Data Availability Section.

### 2.2.1 Coal production

Since 2014, Statistics Canada has ceased publishing complete production data for each coal type, but the US government still does (EIA, 2020; Statistics Canada, 2020a). Therefore, data on Canadian coal from the U.S. *Energy Information Administration* (EIA) was employed. Data for

2020 were missing. According to Statistics Canada, total production decreased by 21.8% in 2020, therefore production levels of 2019 for each coal type decreased by this proportion were adopted as an approximation for 2020.

### **2.2.2 Oil production**

Oil production data comes from the *Canadian Energy Regulator* (CER) (Canadian Energy Regulator, 2021a). McGlade and Ekins (2015) classified oil into conventional and unconventional. Conventional oil includes the CER categories of conventional light crude, conventional heavy crude and condensate while unconventional oil includes synthetic crude oil and non-upgraded Alberta bitumen.

### **2.2.3 Gas production**

Data on marketable natural gas production was also obtained from CER (Canadian Energy Regulator, 2021b). These data lack annual proportions of conventional and unconventional gas. Only the province of *British Columbia* (BC) publishes these proportions, therefore they were used to approximate Canadian production for 2011 to 2019 (BC Oil and Gas Commission, 2020). By fitting a curve through these points, the proportion of unconventional gas was estimated to be about 92% in 2020.

## **2.3 Results**

Table 2 provides the amount of each fossil fuel produced between 2011 and 2020. It computes the percentage of the production budget (from Table 1) that has already been extracted. Fig. 1 shows this percentage for each fossil fuel. During this period, Canada spent 76.3% of its budget of hard coal, 7.4% of its lignite, 33.6% of its conventional oil, 115.8% of its unconventional oil, 23.9% of its conventional gas and 16.8% of its unconventional gas. For unconventional oil, Canada has therefore exceeded its budget for the entire 21<sup>st</sup> century. Indeed, unconventional oil production increased by 84% from 2011 to 2019.

**Table 2**

Canadian fossil fuels produced and percent of budget spent during the 2011-2020 period.

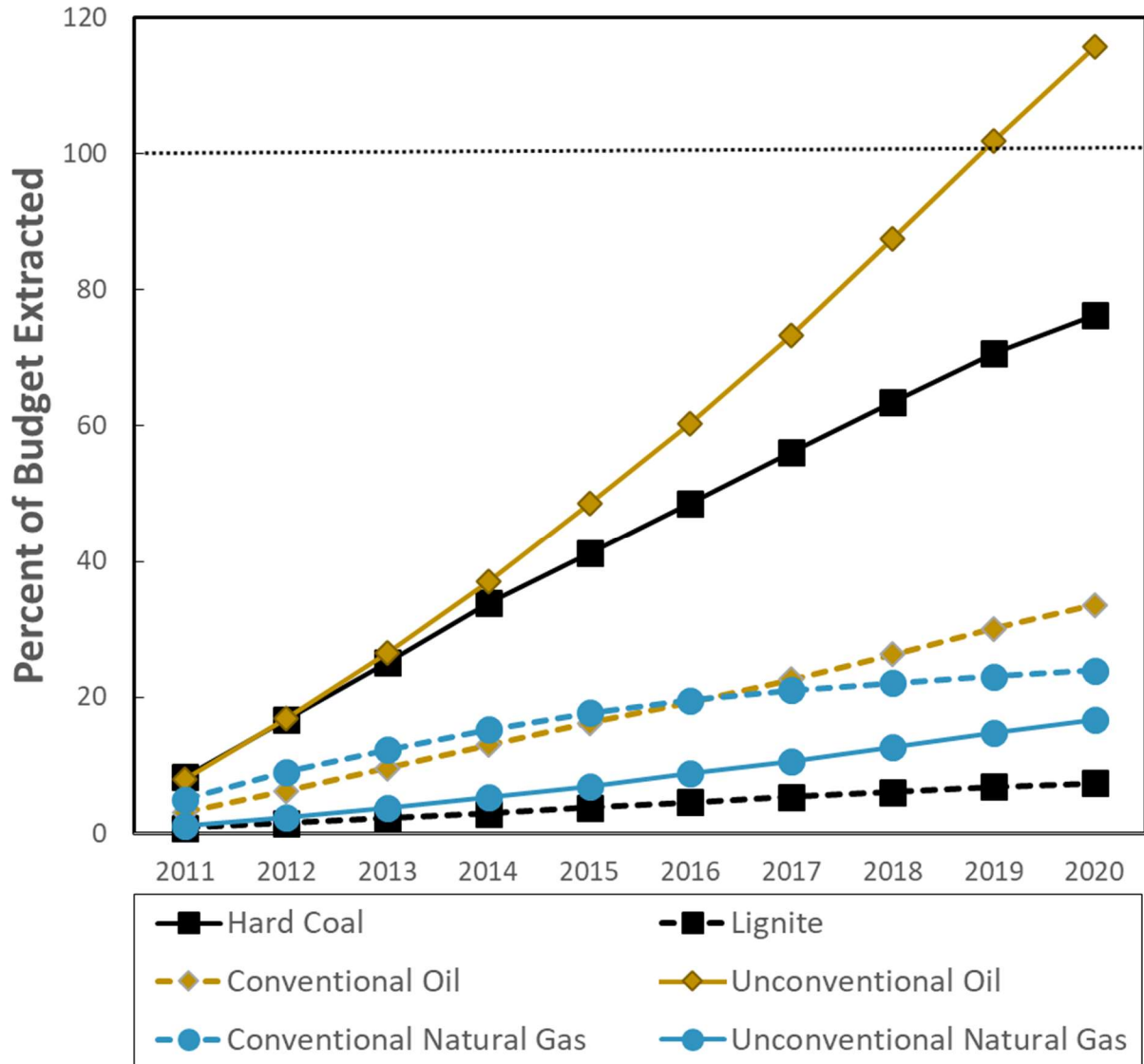
Fossil fuel	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
<b>Hard Coal (Gt)<sup>a</sup></b>	0.058	0.058	0.060	0.061	0.051	0.051	0.053	0.052	0.051	0.040
<b>Hard Coal Cumul. (Gt)</b>	0.058	0.116	0.176	0.237	0.289	0.340	0.392	0.444	0.495	0.534
<b>% of Budget Cumul.</b>	8.3	16.6	25.2	33.9	41.2	48.6	56.1	63.4	70.7	76.3
<b>Lignite (Gt)<sup>a</sup></b>	0.009	0.009	0.009	0.008	0.010	0.010	0.009	0.009	0.009	0.007
<b>Lignite Cumul. (Gt)</b>	0.009	0.017	0.026	0.034	0.045	0.055	0.064	0.073	0.082	0.089
<b>% of Budget Cumul.</b>	0.7	1.4	2.2	2.9	3.7	4.6	5.3	6.1	6.8	7.4
<b>Conv. Oil (Gb)<sup>b</sup></b>	0.510	0.530	0.558	0.576	0.540	0.529	0.557	0.609	0.635	0.597
<b>Conv. Oil Cumul. (Gb)</b>	0.510	1.040	1.598	2.175	2.715	3.243	3.800	4.408	5.043	5.640
<b>% of Budget Cumul.</b>	3.0	6.2	9.5	12.9	16.2	19.3	22.6	26.2	30.0	33.6
<b>Uncon. Oil (Gb)<sup>b</sup></b>	0.597	0.667	0.717	0.793	0.869	0.884	0.976	1.063	1.076	1.040
<b>Uncon. Oil Cumul. (Gb)</b>	0.597	1.265	1.982	2.775	3.644	4.528	5.504	6.567	7.643	8.683
<b>% of Budget Cumul.</b>	8.0	16.9	26.4	37.0	48.6	60.4	73.4	87.6	101.9	115.8
<b>Con. Gas (Tcm) at 15°C<sup>b,c</sup></b>	0.069	0.056	0.047	0.041	0.035	0.025	0.021	0.015	0.013	0.013
<b>Con. Gas Cumul. (Tcm)</b>	0.069	0.126	0.172	0.213	0.248	0.273	0.294	0.309	0.322	0.335
<b>% of Budget Cumul.</b>	5.0	9.0	12.3	15.2	17.7	19.5	21.0	22.1	23.0	23.9
<b>Uncon. Gas (Tcm) at 15°C<sup>b,c</sup></b>	0.081	0.088	0.099	0.112	0.122	0.133	0.140	0.152	0.149	0.147
<b>Uncon. Gas Cumul (Tcm)</b>	0.081	0.169	0.268	0.380	0.502	0.635	0.775	0.927	1.076	1.223
<b>% of Budget Cumul.</b>	1.1	2.3	3.7	5.2	6.9	8.7	10.6	12.7	14.7	16.8

Gt = gigatonne, Gb = gigabarrel, Tcm = trillion cubic meters, Con. = conventional, Uncon. = unconventional, Cumul. = cumulative.

<sup>a</sup>Data from EIA (EIA, 2020).

<sup>b</sup>Data from CER (Canadian Energy Regulator, 2021a, 2021b).

<sup>c</sup>Proportion of conventional versus unconventional natural gas (BC Oil and Gas Commission, 2020).



**Fig 1.** Percentage of the production budget already extracted as a function of time and type of fossil fuel according to the 2°C scenario from McGlade and Ekins' (2015) model.



## **3 Global GHG emissions from Canadian fossil fuel production**

### **3.1 Introduction**

Are the global emissions of the Canadian fossil fuel industry decreasing? To assess these global emissions, one has to use emission factors obtained with LCA for each type of fossil fuel extracted in Canada. This analysis includes emissions during extraction, transformation, transportation and combustion, whether or not the fuel is exported. One limit of this section is that calculations do not include fossil fuels imported into Canada to be transformed or burned, but only those extracted in Canada. However, calculations in the next section include emissions of imported fuel and exclude downstream emissions of exported fuels.

### **3.2 Methods**

#### **3.2.1 Introduction**

The selection of the proper emission factors for each type of fossil fuel is described below. Efforts were made to use emission factors developed or adapted to Canadian fossil fuels conditions. All factors referenced in this paper were computed using *Global Warming Potential* (GWP) with a horizon of 100 years (GWP100) after emission of the GHG.

#### **3.2.2 Coal emissions**

There are only a few publications on GHG emissions of Canadian coal (Jaques, 1992; Martin et al., 2004; The Climate Registry, 2020). The Canadian National Inventory Report 2021 submitted to the *United Nations Framework Convention on Climate Change* (UNFCCC) written by the Ministry of *Environment and Climate Change Canada* (ECCC) was adopted (ECCC, 2021). This document provides CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions from different coal production processes, but does not combine them to produce a single emission factor expressed in CO<sub>2</sub>-equivalent for each coal type. This is accomplished in the following paragraphs, starting with the chemical analysis of the carbon content of each coal type. Table 3 (column ‘CO<sub>2</sub> only’) shows that CO<sub>2</sub> emissions are the following in tCO<sub>2</sub>/tonne: 2.198 for bituminous coal from Alberta, 1.763 for sub-bituminous coal, and 1.460 for lignite. Note that Canada does not currently produce anthracite.

**Table 3**

Computations of emission factors for different types of Canadian coal.

	<b>Total</b> <b>(tCO<sub>2</sub>e/tonne)</b>	<b>CO<sub>2</sub> only</b> <b>(tCO<sub>2</sub>/tonne)</b>	<b>CH<sub>4</sub> from</b> <b>mining</b> <b>(tCO<sub>2</sub>e/tonne)</b>	<b>CH<sub>4</sub> and N<sub>2</sub>O</b> <b>from use</b> <b>(tCO<sub>2</sub>e/tonne)</b>
<b>Bituminous</b>	<b>2.241</b>	2.198 <sup>a</sup>	0.036 <sup>a</sup>	0.007 <sup>a</sup>
<b>Sub-Bituminous</b>	<b>1.782</b>	1.763 <sup>a</sup>	0.010 <sup>a</sup>	0.009 <sup>a</sup>
<b>Lignite</b>	<b>1.473</b>	1.460 <sup>a</sup>	0.004 <sup>a</sup>	0.009 <sup>a</sup>
<b>Bituminous Metallurgical</b>	<b>2.763</b>	2.720 <sup>b</sup>	0.036 <sup>a</sup>	0.007 <sup>a</sup>
<b>Bituminous Thermal</b>	<b>2.375</b>	2.332 <sup>b</sup>	0.036 <sup>a</sup>	0.007 <sup>a</sup>

tCO<sub>2</sub>e/tonne = tonnes of CO<sub>2</sub>-equivalent per tonne of coal.

<sup>a</sup>Computed with data from ECCC (ECCC, 2020a).

<sup>b</sup>Computed with data from EPA (EPA, 2013).

There are several issues with ECCC's factors. Firstly, they do not differentiate between metallurgical and thermal bituminous coal. Secondly, no measures were taken on coal from BC, which produces 48% of Canadian coal (Natural Resources Canada, 2017). To remediate these issues, US emission factors from EPA were adopted as an approximation. This substitution is acceptable because CO<sub>2</sub> release depends on carbon content, whose range is standard for a given coal rank. Thus, the EPA emission factor of 2.720 tCO<sub>2</sub>/tonne for industrial coking was adopted for metallurgical coal and the factor of 2.332 tCO<sub>2</sub>/tonne for the industrial sector was adopted for thermal coal (EPA, 2013). Note that the production statistics for bituminous metallurgical coal include the coal used to make coke.

Thirdly, the emissions mentioned above are only for carbon dioxide (CO<sub>2</sub>), therefore the impact of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) has to be added using data from ECCC. Given that almost all Canadian coal mines are now surface mines, only the fugitive emissions from surface mining were considered. These emissions amount (in kgCH<sub>4</sub>/tonne) to 0.705 for gross bituminous coal (i.e., Run-Of-Mine or ROM), 0.2 for gross sub-bituminous coal and 0.07 for gross lignite. Averaging across seven Canadian mining projects, shows that it takes about 1.607 tonnes of ROM to make one tonne of clean coal (Canadian Mining Journal Staff, 2018; Coalspur Mines Limited, 2012; Colonial Coal International Corp., 2019; CST Canada Coal Limited, 2019; Hunter and Gilron, 2013; Marston Canada Ltd., 2008; Ram River Coal Corp., 2021). Therefore, emissions

for clean coal are obtained by multiplying emissions for ROM by 1.607 leading to 1.133 kgCH<sub>4</sub>/tonne for bituminous coal, 0.321 for sub-bituminous coal and 0.112 for lignite.

There are also emissions related to the way coal is used. ECCC found that using coal for electric utilities emits 0.02 kgCH<sub>4</sub>/tonne and 0.03 kgN<sub>2</sub>O/tonne; industry, heat and steam plants emit 0.03 kgCH<sub>4</sub>/tonne and 0.02 kgN<sub>2</sub>O/tonne; finally, residential and public administration emit 4 kgCH<sub>4</sub>/tonne and 0.02 kgN<sub>2</sub>O/tonne. It is assumed that all bituminous coal is used for industry, heat and steam plants. It is also assumed that all sub-bituminous coal and lignite are used for electric utilities. These are conservative assumptions given that no residential use was attributed.

The emissions of methane and N<sub>2</sub>O are converted to CO<sub>2</sub>-equivalent using the following GWP100 coefficients: 32 and 282, respectively. These coefficients are from the *Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5)* with climate-carbon feedback (Edenhofer et al., 2014). These values are taken in the middle of the ranges recommended by EPA, that is, 28-36 for methane and 265–298 for nitrous oxide (EPA, 2016). For example, the emission factor for lignite equals 1.4727 tCO<sub>2</sub>e/tonne of lignite = 1.460 tCO<sub>2</sub>e/tonne + ((0.112 kgCH<sub>4</sub>/tonne + 0.02 kgCH<sub>4</sub>/tonne) × 32 kgCO<sub>2</sub>e/kgCH<sub>4</sub> × 0.001 tonne/kg) + (0.03 kgN<sub>2</sub>O/tonne × 282 kgCO<sub>2</sub>e/kgN<sub>2</sub>O × 0.001 tonne/kg). Emission factors for each coal type are presented in Table 3.

Table 1 computes emissions for all Canadian fossil fuel resources. The emission factor for hard coal applied in Table 1 is a weighted sum of the factors for bituminous metallurgical coal, bituminous thermal and sub-bituminous coal. The number of tonnes produced for a coal type in 2019 is employed as a weight. That year is selected because it is the latest year with complete production data. The emission factor obtained for hard coal is 2.487 tCO<sub>2</sub>e/tonne.

Although emission factors used in Table 1 are optimal to evaluate emissions from a part of resources (e.g., column “CO<sub>2</sub> to emit”), they might overestimate emissions from the entire resources (RURR). A much more conservative evaluation of emissions linked to the RURR consists in taking into account only downstream emissions. By summing the columns ‘CO<sub>2</sub>’ and ‘use’ of Table 3 and computing the weighted sum for hard coal, one obtains the downstream emission factors of 2.457 and 1.469 tCO<sub>2</sub>e/tonne for hard coal and lignite, respectively.

### **3.2.3 Oil emissions**

Researchers during the last decade have revised emissions of Canadian oil extraction upward (Gordon et al., 2015; IEA, 2010; IHS CERA, 2010; Koomey and Koomey, 2015). LCA emission

factors were obtained from the most recent and sophisticated model, that is, the *Global Oil-Climate-Index* (OCI) (Gordon et al., 2015; Koomey and Koomey, 2015). The most recent studies suggest that emission factors from OCI could still be too low because fugitive emissions have been underestimated (Atherton et al., 2017; Baray et al., 2018; Chan et al., 2020; Li et al., 2017; Liggio et al., 2019; MacKay et al., 2021; Zavala-Araiza et al., 2018; Zhang et al., 2020). However, OCI was adopted because it provides the most accurate coefficients available.

OCI integrates prior models such as OPGEE and PRELIM while adding another layer called OPEM which takes into account downstream emissions. OPEM computes GHG from transport to consumers, burning of gasoline, diesel, jet fuel, residual fuel and liquefied petroleum gas. Emissions for other petroleum products are not included, such as petcoke, fuel oil, bunker fuel and asphalt.

Some assumptions were made to match existing coefficients of OCI with CER oil categories. Emissions of 487 kgCO<sub>2</sub>e/barrel for Hibernia oil was applied to all conventional light oil. To estimate emissions of synthetic crude oil, the average of five brands was adopted, that is, 754 kgCO<sub>2</sub>e/barrel. For non-upgraded bitumen, the average of three brands of dilbit was adopted: 634 kgCO<sub>2</sub>e/barrel. As this database did not provide an emission factor for conventional heavy Canadian crude oil, the coefficient of 520 kgCO<sub>2</sub>e/barrel for Canada Midale oil was adopted because its density is similar.

No coefficient for condensate (i.e., pentanes plus) was available. As it is extracted in a similar manner as conventional light crude oil, it was assumed that emissions differ only for the combustion phase. EPA published data showing that the combustion of one gallon of pentanes plus emits less CO<sub>2</sub> (2.59 kg/gallon less), less CH<sub>4</sub> (0.08 g/gallon less) and less N<sub>2</sub>O (0.01 g/gallon less) than crude oil (Environmental Protection Agency, 2018). Thus, GHG in CO<sub>2</sub>-equivalent for pentane plus are inferior by 109 kgCO<sub>2</sub>e/barrel to emissions of conventional crude oil. This number is obtained in the following way:  $2590 \text{ gCO}_2/\text{gallon} + (0.08 \text{ gCH}_4/\text{gallon} \times 32 \text{ gCO}_2\text{e}/\text{gCH}_4) + (0.01 \text{ gN}_2\text{O}/\text{gallon} \times 282 \text{ gCO}_2\text{e}/\text{gN}_2\text{O}) = 2595 \text{ gCO}_2\text{e}/\text{gallon}$ , where 32 and 282 are the GWP100 for methane and nitrous oxide, respectively (EPA, 2016). Converting from gallons to barrels, one obtains 109 kgCO<sub>2</sub>e/barrel (i.e., 2.60 kg/gallon × 42 gallons/barrel). Therefore, the emission factor of condensate is 378 kgCO<sub>2</sub>e/barrel, that is, 487 kgCO<sub>2</sub>e/barrel – 109 kgCO<sub>2</sub>e/barrel, where 487 kgCO<sub>2</sub>e/barrel is the emission factor of conventional light crude oil.

To compute GHG from oil in Table 1, emission factors for conventional and unconventional oil were computed as a weighted sum of the previous coefficients using the number of barrels produced in 2019 as weights. For example, in the case of conventional oil the emission factor of 470 kgCO<sub>2e</sub>/barrel is equal to (0.289 Gb of conventional light crude × 487 kgCO<sub>2e</sub>/barrel + 0.188 Gb of conventional heavy crude × 520 kgCO<sub>2e</sub>/barrel + 0.158 Gb of condensate × 378 kgCO<sub>2e</sub>/barrel) / (0.289 Gb + 0.188 Gb + 0.158 Gb). A corresponding weighted sum equals 679 kgCO<sub>2e</sub>/barrel for unconventional oil.

To compute a more conservative evaluation of GHG from the RURR, as explained for coal above, the downstream emission factors are necessary. They are in kgCO<sub>2e</sub>/barrel: 436 for conventional crude oil (Hibernia), 426 for conventional heavy oil (Midale), 209 for condensate (pentanes plus), 539 for upgraded-bitumen (from 5 brands), 455 for non-upgraded bitumen (3 brands of dilbit) (EIA, 2016; Gordon et al., 2015; Koomey and Koomey, 2015). Weighted sums with these emission factors using the number of barrels produced in 2019 as weights result in the following downstream emission factors in kgCO<sub>2e</sub>/barrel: 376 for conventional and 486 for unconventional oil.

### **3.2.4 Gas emissions**

Most literature reviews have shown no significant difference between the LCA emissions of conventional gas compared to shale gas, although this is still debated (Balcombe et al., 2017; Burnham et al., 2012; Weber and Clavin, 2012). Consequently, the same coefficient is used for both types of gas. Because production volumes are reported at 15 °C and emission factors apply to gas at 0 °C, volumes were converted with the ideal gas equation to 0 °C and 1 atmosphere.

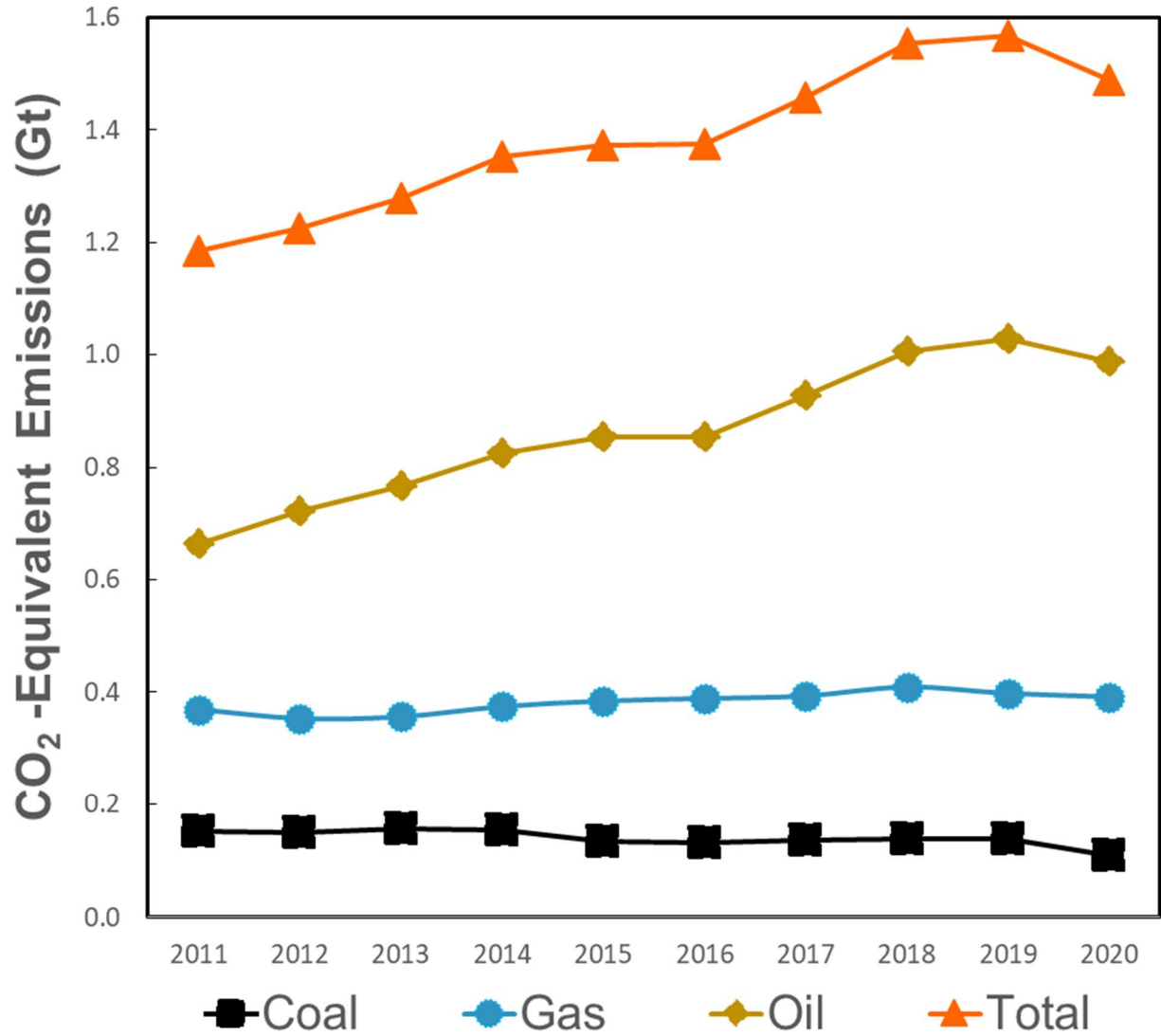
The emission factor for natural gas is construed as the sum of two numbers: upstream and downstream. Downstream, burning Canadian natural gas emits 1.926 kgCO<sub>2e</sub>/m<sup>3</sup>. This number is obtained by averaging across various compositions from all producing provinces (Environment Canada, 2011). A study showed that the upstream emissions (pre-production, extraction, processing, transmission, storage & distribution) are equal to 0.357 kgCO<sub>2e</sub>/m<sup>3</sup> assuming 0.97% leaking of methane during this process (Balcombe et al., 2017). Recent studies in the U.S. have shown that 2.3% of leaking is more realistic during these steps (Alvarez et al., 2018). Other studies in Canada confirm that this evaluation is conservative and could even reach 3.7% for U.S. and Canada (Howarth, 2019; Zhang et al., 2020). The intermediate value of 2.3% leak rate was adopted, which leads to a correction of 0.305 kgCO<sub>2e</sub>/m<sup>3</sup>. It is obtained with the following

calculation:  $0.717 \text{ kgCH}_4/\text{m}^3 \times (0.023 - 0.0097) \times 32 \text{ kgCO}_2\text{e}/\text{kgCH}_4$ , where  $0.717 \text{ kgCH}_4/\text{m}^3$  is the density of methane at  $0^\circ\text{C}$  and 1 atmosphere and 32 is the GWP100 of methane (EPA, 2016). The total is  $2.587 \text{ kgCO}_2\text{e}/\text{m}^3$ .

### 3.3 Results

Table 1 shows that the amount of GHG that Canada is allowed to emit according to the McGlade and Ekins (2015) model is  $37.6 \text{ GtCO}_2\text{-equivalent (GtCO}_2\text{e)}$  assuming conditions similar to those of 2019. Table 1 shows that if the totality of Canadian fossil fuel resources (RURR) was exploited, this would generate GHG emissions of  $682 \text{ GtCO}_2\text{e}$  assuming conditions similar to those of 2019. By using the more conservative factors taking into account only downstream emissions, one obtains  $533 \text{ GtCO}_2\text{e}$  for RURR.

Fig. 2 illustrates that oil is the main source of GHG emissions, followed by gas and then coal. Table 4 shows emissions from coal, oil and gas. In 2019, global emissions from coal represented  $0.139 \text{ GtCO}_2\text{e}$ , from conventional oil  $0.298$ , from unconventional oil  $0.731$  and from natural gas  $0.398$ . The total amount of GHG emitted by the exploitation of Canadian fossil fuels has increased from  $1.186 \text{ GtCO}_2\text{e}$  in 2011 to  $1.566$  in 2019 and decreased to  $1.489$  in 2020. This represents a 32% increase from 2011 to 2019 followed by a 4.9% drop in 2020. Over the 2011-2020 period an amount of  $13.86 \text{ GtCO}_2\text{e}$  has been spent out of a CB of  $37.6 \text{ GtCO}_2\text{e}$  (from Table 1). This means that 37% of the fossil fuel budget for the 21<sup>st</sup> century has been spent in 10 years.



**Fig. 2.** Global emissions of CO<sub>2</sub>-equivalent as a function of time for coal, (natural) gas, oil as well as total emissions.

**Table 4**

Fossil fuel production and CO<sub>2</sub>-equivalent emissions using LCA.

FOSSIL FUELS	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
<b>Metallurgical Bit. Coal (Gt)</b>	0.033	0.033	0.034	0.032	0.026	0.025	0.028	0.032	0.034	0.027
<b>CO<sub>2</sub>e (Gt)</b>	0.092	0.091	0.094	0.088	0.072	0.069	0.078	0.089	0.094	0.073
<b>Thermal Bit. Coal (Gt)</b>	0.004	0.004	0.004	0.004	0.003	0.003	0.003	0.003	0.004	0.003
<b>CO<sub>2</sub>e (Gt)</b>	0.010	0.010	0.010	0.010	0.007	0.007	0.008	0.008	0.010	0.008
<b>Sub-Bituminous Coal (Gt)</b>	0.021	0.021	0.022	0.025	0.022	0.024	0.021	0.016	0.013	0.010
<b>CO<sub>2</sub>e (Gt)</b>	0.038	0.037	0.039	0.045	0.040	0.042	0.038	0.028	0.023	0.018
<b>Lignite (Gt)</b>	0.009	0.009	0.009	0.008	0.010	0.010	0.009	0.009	0.009	0.007
<b>CO<sub>2</sub>e (Gt)</b>	0.013	0.013	0.013	0.012	0.015	0.015	0.013	0.013	0.013	0.010
<b>TOTAL COAL (Gt)</b>	0.067	0.066	0.069	0.069	0.062	0.061	0.062	0.060	0.060	0.047
<b>CO<sub>2</sub>e (Gt)</b>	0.152	0.150	0.156	0.154	0.134	0.132	0.137	0.138	0.139	0.109
<b>Con. Light Crude (Gb)</b>	0.303	0.314	0.338	0.342	0.304	0.287	0.294	0.295	0.288	0.253
<b>CO<sub>2</sub>e (Gt)</b>	0.147	0.153	0.165	0.167	0.148	0.140	0.143	0.144	0.140	0.123
<b>Con. Heavy Crude (Gb)</b>	0.157	0.167	0.167	0.170	0.158	0.147	0.149	0.170	0.188	0.185
<b>CO<sub>2</sub>e (Gt)</b>	0.081	0.087	0.087	0.089	0.082	0.077	0.078	0.088	0.098	0.096
<b>Condensate (Gb)</b>	0.050	0.050	0.053	0.064	0.078	0.094	0.114	0.144	0.159	0.158
<b>CO<sub>2</sub>e (Gt)</b>	0.019	0.019	0.020	0.024	0.029	0.036	0.043	0.054	0.060	0.060
<b>TOTAL CON. OIL (Gb)</b>	0.510	0.530	0.558	0.576	0.540	0.529	0.557	0.609	0.635	0.597
<b>CO<sub>2</sub>e (Gt)</b>	0.248	0.258	0.272	0.279	0.260	0.252	0.264	0.286	0.298	0.280
<b>Upgraded Bitumen (Gb)</b>	0.311	0.334	0.341	0.348	0.356	0.340	0.375	0.386	0.405	0.410
<b>CO<sub>2</sub>e (Gt)</b>	0.234	0.252	0.257	0.262	0.268	0.256	0.282	0.291	0.306	0.309
<b>Non-upgraded Bitumen (Gb)</b>	0.287	0.333	0.376	0.446	0.513	0.543	0.601	0.678	0.671	0.631
<b>CO<sub>2</sub>e (Gt)</b>	0.182	0.211	0.238	0.282	0.325	0.345	0.381	0.430	0.425	0.400
<b>TOTAL UNCON. OIL (Gb)</b>	0.597	0.667	0.717	0.793	0.869	0.884	0.976	1.063	1.076	1.040
<b>CO<sub>2</sub>e (Gt)</b>	0.416	0.463	0.496	0.545	0.594	0.601	0.664	0.720	0.731	0.709
<b>TOTAL OIL (Gb)</b>	1.107	1.198	1.275	1.370	1.409	1.412	1.533	1.672	1.711	1.637
<b>CO<sub>2</sub>e (Gt)</b>	0.664	0.721	0.767	0.824	0.853	0.853	0.927	1.007	1.029	0.988
<b>Con. Gas at 0 °C (Tcm)</b>	0.066	0.053	0.044	0.039	0.033	0.024	0.020	0.014	0.012	0.012
<b>CO<sub>2</sub>e (Gt)</b>	0.170	0.138	0.114	0.101	0.085	0.062	0.051	0.037	0.032	0.031
<b>Uncon. Gas at 0 °C (Tcm)</b>	0.077	0.083	0.094	0.106	0.116	0.126	0.132	0.144	0.142	0.139
<b>CO<sub>2</sub>e (Gt)</b>	0.200	0.216	0.243	0.274	0.300	0.327	0.342	0.373	0.366	0.361
<b>TOTAL GAS AT 0 °C (Tcm)</b>	0.143	0.137	0.138	0.145	0.149	0.150	0.152	0.158	0.154	0.152
<b>CO<sub>2</sub>e (Gt)</b>	0.370	0.354	0.357	0.375	0.385	0.389	0.394	0.410	0.398	0.392
<b>TOTAL CO<sub>2</sub>e (Gt)</b>	1.186	1.226	1.280	1.353	1.372	1.375	1.458	1.555	1.566	1.489
<b>TOTAL CUMUL. CO<sub>2</sub>e (Gt)</b>	1.186	2.411	3.691	5.044	6.416	7.791	9.249	10.803	12.370	13.859

LCA = Life Cycle Analysis. CO<sub>2</sub>e = CO<sub>2</sub>-equivalent, Gt = gigatonne, Gb = gigabarrel, Tcm = Trillion Cubic Meter, Bit. = bituminous, Con. = conventional, Uncon. = unconventional, Cumul. = cumulative.



Table 4 reveals that most of the emissions increase is due to unconventional oil which increased from 0.416 to 0.731 GtCO<sub>2e</sub> annually from 2011 to 2019. Emissions from natural gas have increased by 0.028 GtCO<sub>2e</sub> from 2011 to 2019, which is more than the decrease in coal emissions of 0.013 GtCO<sub>2e</sub> over that period.

## 4 Canadian national carbon budget

### 4.1 Introduction

Do Canadian national emissions respect the CB proposed by different models simulating the 2.0 °C scenario? One difficulty in answering this question is that there is no commonly accepted CB. Three models that calculated a CB specifically for Canada under the 2°C scenario are analysed below (Alcaraz et al., 2018; Gignac and Matthews, 2015; Kanitkar et al., 2013). These analyses complement the LCA fossil fuel emissions presented in the previous section because these models focus on national emissions, which include imported fossil fuels and exclude the combustion of fossil fuels extracted in Canada but burned after exportation.

### 4.2 Methods

To evaluate a specific model, the same emissions database as the model was used. The *Model of Climate Justice* (MCJ) and the *Tata Institute of Social Sciences - Delhi Science Forum* (TISS-DSF) model used the *Climate Analysis Indicator Tool* (CAIT) (Alcaraz et al., 2018; Climate Watch, 2020; Kanitkar et al., 2013). The model proposed by Gignac and Matthews (2015), or G&M, used the *Carbon Dioxide Information Analysis Center* (CDIAC) database (Boden et al., 2015). The MCJ and G&M models excluded *Land Use, Land-Use Change and Forestry* (LULUCF), while the TISS-DSF included it. Because the CAIT only has data until 2017 and CDIAC until 2014, data for the missing years had to be estimated. Although estimations could lack precision, it is valuable for policy evaluation to have at least a reasonable estimate of the CB spent.

To estimate missing data with credible values, ECCC emissions data from the Canadian government were used because they are available until 2019 inclusively (ECCC, 2021). The percent change from one year to the next using ECCC emissions excluding LULUCF was used to predict each missing year. Tests were performed to assess the precision of these estimations. For

CAIT excluding LULUCF, the average absolute value of the error in predicting the sum of three years of emissions over the 1990-2017 period using ECCC data is 0.83%. For CAIT including LULUCF, this error equals 5.2% (5.8% when using ECCC with LULUCF). For CDIAC excluding LULUCF, the average error in predicting the sum of six years of emissions over the 1990-2014 period is 1.2%.

In 2020, the COVID-19 pandemic caused an important drop of GHG emissions globally of 7% (Friedlingstein et al., 2020). Consistently, Table 4 shows that the global GHG emissions of the Canadian fossil fuel industry dropped by 4.9% in 2020. Therefore, a conservative drop of 7% was assumed for ECCC, CAIT and CDIAC in 2020. Historical and extrapolated data are shown in Table 5.

**Table 5**

Historical and estimated GHG emissions for Canada according to three sources.

GHG Emissions (GtCO <sub>2</sub> e)	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
<b>ECCC Excluding LULUCF</b>	0.703	0.714	0.717	0.725	0.723	0.723	0.707	0.716	0.728	0.730	<b>0.679</b>
<b>ECCC Including LULUCF</b>	0.696	0.708	0.708	0.721	0.720	0.727	0.707	0.717	0.736	0.740	<b>0.688</b>
<b>CAIT Excluding LULUCF</b>	0.674	0.689	0.694	0.705	0.712	0.708	0.695	0.709	<b>0.721</b>	<b>0.723</b>	<b>0.672</b>
<b>CAIT Including LULUCF</b>	0.653	0.649	0.664	0.662	0.683	0.698	0.693	0.690	<b>0.701</b>	<b>0.703</b>	<b>0.654</b>
<b>CDIAC Excluding LULUCF</b>	0.540	0.542	0.522	0.521	0.541	<b>0.541</b>	<b>0.529</b>	<b>0.535</b>	<b>0.544</b>	<b>0.546</b>	<b>0.508</b>

ECCC: Environment and Climate Change Canada, LULUCF: Land Use, Land-Use Change and Forestry, CAIT: Climate Analysis Indicator Tool, CDIAC: Carbon Dioxide Information Analysis Center. Data in **bold** are estimated.

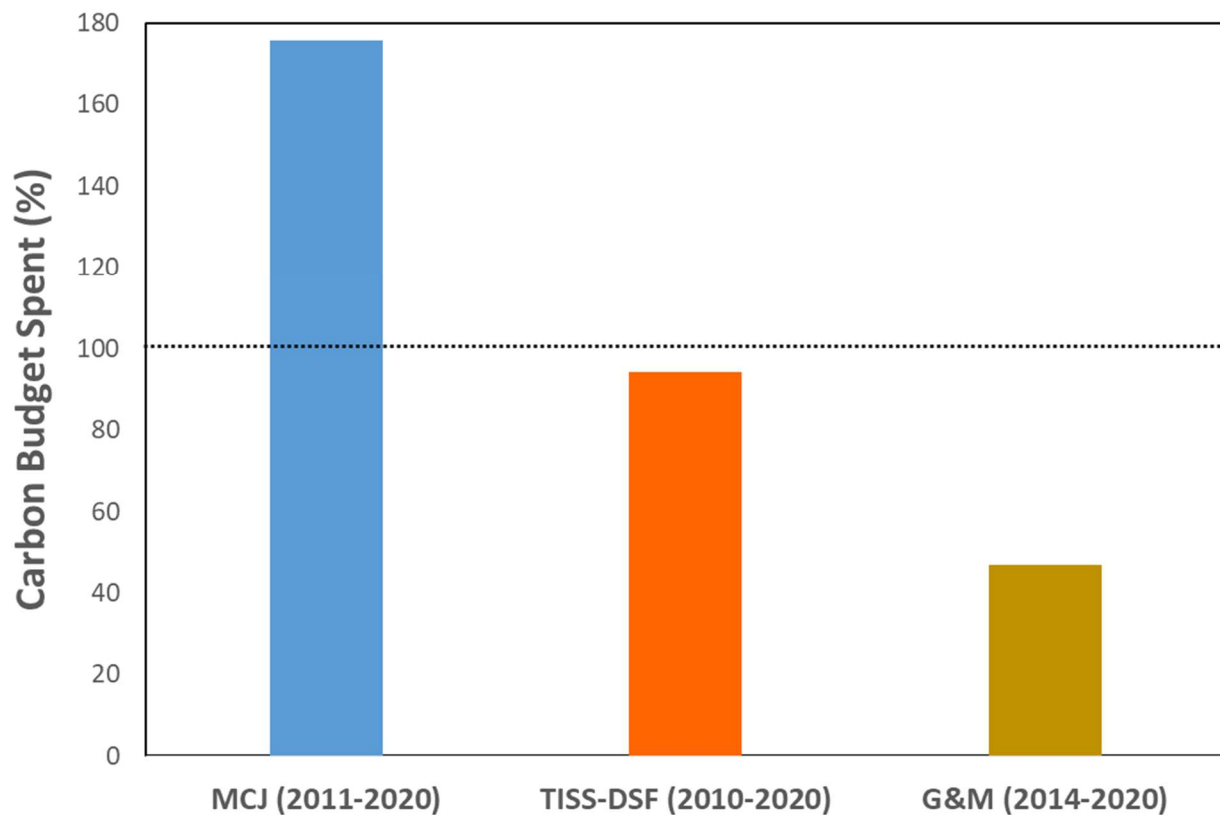
## 4.3 MCJ model

### 4.3.1 Introduction

MCJ is a model taking into account equity (Alcaraz et al., 2018). The annual responsibility of a country is defined as the per capita emissions of CO<sub>2</sub> minus the world average. They take 1992 as the starting date and use the *Representative Concentration Pathways* scenario with 2.6 W/m<sup>2</sup> (RCP2.6) from IPCC AR5 (Edenhofer et al., 2014), which provides a GCB of 1057 GtCO<sub>2</sub> within the 2°C objective. The MCJ model evolves countries' emissions inversely to their responsibility factor starting in 2013. Emissions per capita for all countries converge toward the yearly average. The MCJ predicts a Canadian CB of 4.0 GtCO<sub>2</sub>e from 2011 to 2100.

### 4.3.2 Results

The sum of the extrapolated data from CAIT excluding LULUCF, in Table 5, equals 7.029 GtCO<sub>2e</sub> over the 2011-2020 period. Therefore, according to the MCJ model, Canada has already spent more than its CB for the 21<sup>st</sup> century. This is showed in Fig. 3.



**Fig. 3.** Percentage of the Canadian *carbon budget* (CB) for the 21<sup>st</sup> century already spent according to three models: *Model of Climate Justice* (MCJ), *Tata Institute of Social Sciences - Delhi Science Forum* (TISS-DSF) and *Gignac and Matthews* (G&M).

## 4.4 TISS-DSF model

### 4.4.1 Introduction

Kanitkar et al. (2013) distributed the GCB among regions using their TISS-DSF model (Kanitkar et al., 2013). They used the upper limit of GCB from 2010-2050 following the 2°C scenario. Fair share of the GCB for a given region was defined as proportional to its population. Entitlement designates the portion of the fair share that a region is allowed in a specified time period. The

TISS-DSF model computes future entitlement by subtracting each region's historical emissions from its fair share. A negative future entitlement, implies that a region must reduce its emissions. The model allocates a quota of 7.92 GtCO<sub>2e</sub> to Canada from 2010 to 2050.

#### **4.4.2 Results**

The sum of the extrapolated data from CAIT including LULUCF in Table 5 over the 2010-2020 period equals 7.451 GtCO<sub>2e</sub>. Therefore, according to the TISS-DSF Model, Canada has spent 94.1% of its CB for the 2010-2050 period as showed in Fig. 3. This implies that Canada's CB will be exhausted by the end of 2021 because the 0.469 GtCO<sub>2e</sub> left is much lower than the annual national emissions of 0.679 GtCO<sub>2e</sub> in 2020.

### **4.5 G&M model**

#### **4.5.1 Introduction**

The G&M model follows the RCP2.6 scenario consistent with a 67% chance of limiting temperature rise to 2°C by 2100 (Gignac and Matthews, 2015). Their model follows the *Contraction and Convergence* framework where emissions converge toward a point of equal per capita emissions across nations at a given date. After this point, per capita emissions decrease toward zero at a further date (Meyer, 2000). They simulated two scenarios, both taking 2014 as the starting point, one taking 2035 as the convergence date and the other, 2050. They obtained a Canadian CB of 8 GtCO<sub>2e</sub> in the first scenario and of 10 GtCO<sub>2</sub> in the second. Their 2035 convergence point scenario implies that per capita emissions drop 0.56 tonnes yearly, from 14.8 tonnes in 2013 to 2.4 tonnes in 2035.

Table 6 shows the data relevant to the 2035 scenario of the G&M model. Initial emissions equal 0.521 GtCO<sub>2e</sub>. Dividing by the population leads to an initial value of 14.8 tCO<sub>2e</sub>/capita (United Nations, 2019). By reducing this amount by 0.56 tCO<sub>2e</sub> every year, one obtains the per capita target emissions until 2035. By multiplying by the population, one finds the target national emissions (in GtCO<sub>2e</sub>/year).

**Table 6**

Canadian emissions compared to the annual targets of the G&M model.

	2013	2014	2015	2016	2017	2018	2019	2020
<b>Emissions CDIAc Excluding LULUCF (GtCO<sub>2</sub>e)</b>	0.521	0.541	<b>0.541</b>	<b>0.529</b>	<b>0.535</b>	<b>0.544</b>	<b>0.546</b>	<b>0.508</b>
<b>Canadian Population (thousands)<sup>a</sup></b>	35297	35664	36027	36383	36732	37075	37411	37742
<b>Target Emissions Per Capita (tonne of CO<sub>2</sub>e/person)</b>	14.8	14.2	13.6	13.1	12.5	12.0	11.4	10.8
<b>Target Emissions (GtCO<sub>2</sub>e)</b>	0.521	0.506	0.491	0.476	0.460	0.443	0.426	0.409

CDIAc: Carbon Dioxide Information Analysis Center, LULUCF: Land Use, Land-Use Change, and Forestry, GtCO<sub>2</sub>e: Gigatonne of CO<sub>2</sub>-equivalent.

Data in **bold** are extrapolated.

<sup>a</sup>Population data is from United Nations World Population Prospects 2019.

## 4.5.2 Results

The sum of extrapolated CDIAc data excluding LULUCF (in Table 6) from 2014 to 2020 equals 3.74 GtCO<sub>2</sub>. This represents 47% of the budget from the 2014-2035 scenario (see Fig. 3) and 37% of the budget from the 2014-2050 scenario. According to this model, Canada has not exhausted its CB. However, have Canadian per capita emissions been decreasing yearly by 0.56 tonnes since 2014? As shown in Table 6, from 2014 to 2020 the extrapolated emissions are higher than targets for every year. The sum of the target emissions from 2014 to 2020, in Table 6, equals 3.21 GtCO<sub>2</sub>e and the sum of extrapolated emissions equals 3.74 GtCO<sub>2</sub>e. Therefore, cumulative emissions are 16.6% higher than the targets.

## 5 Conclusion and policy implications

As Canadian annual unconventional oil production increased by 80% from 2011 to 2019 - reaching 1.08 gigabarrels (Gb) - Canada's cumulative production over that period exceeded the 7.5 Gb budget set by McGlade and Ekins' (2015) model. Unconventional oil extracted after 2019 represents 'unburnable oil', that is, oil that is beyond the upper limit of the 2°C scenario. Yet, in 2018 the federal government bought the TransMountain pipeline for 4.5 billion *Canadian dollars* (CAD \$) and is building a new one, making it possible to increase production by 0.215 Gb annually (Morgan, 2018; TransMountain, 2017). In 2020, the federal government also scaled back

environmental assessment of offshore oil exploration, with the stated goal of shortening the average delay from 905 days to 90 days (Quinn, 2020). A 2018 report found that Canada provided more financial support to fossil fuel companies than any other G7 country (Whitley et al., 2018). During 2020, invoking the COVID-19 pandemic, the federal government increased subsidies for oil and gas by 200% reaching at least 1.9 billion CAD \$ (Corkal, 2021).

There are, however, factors that could force a decrease in future oil production, such as American political and legal decisions. For example, on the day he took office, US president Joe Biden revoked the license to build Phase IV of the Keystone XL Pipeline which would have carried annually an extra 0.182 Gb to the US (CBC News, 2021; Monga, 2018). The governor of Michigan has recently issued an order to close the Enbridge Line 5 pipeline, which carries about 0.197 Gb of oil from Canada to the US each year. The company's challenge of this order is currently before the US Federal Court (The Associated Press, 2021).

Canada has already extracted 76.3% of the hard coal budget proposed by McGlade and Ekins (2015). At the pace of 2019, this budget will be exhausted by the end of 2023. As a member of the *Powering Past Coal Alliance* (PPCA), Canada is phasing out coal power generation on its territory (PPCA, 2021). However, the extraction of metallurgical coal is promoted for exports (Fletcher, 2021). It is supported by exploration tax credits for coal mines in BC (BC Government, 2020). Indeed, investments in exploration for new coal mines totaled 70 million CAD \$ in 2018 (Natural Resources Canada, 2018). Vancouver has a project to expand a coal terminal in its harbour to increase exports (Royal Vancouver Yacht Club, 2020). One possible factor motivating this expansion project is that Vancouver accepts American coal for export while the neighboring states of Washington and Oregon have blocked all proposed coal terminals during the last decade (Kerr, 2019).

Canada's gas production increased by 7.6% from 2011 to 2019. This production is likely to increase further because the federal government has issued long-term export licenses to 24 *Liquefied Natural Gas* (LNG) terminal projects ranging between 20-40 years (Natural Resources Canada, 2020a). Their projected peak production is 0.30 Tcm/year, which would triple production and lead to GHG emissions higher than 2020 emissions from oil. The first Canadian LNG export terminals are scheduled to be in operation at Goldboro in Nova-Scotia and Kitimat (BC) around 2024 and 2025, respectively (Global Energy Monitor Wikipedia, 2021; Jang, 2021). Domestic consumption of natural gas has increased by 36% from 2010 to 2019, partly because Ontario

replaced its coal power generation plants with natural gas combined cycle plants (BP, 2020). Alberta plans to do the same (Healing, 2020).

The conversion from coal to natural gas is underway even though it is ill advised. Instead of a reduction, it could be very well be an increase. Given that the methane leak rate is in the 2.3%-3.7% range, if one applies a horizon of 20 years to compute the impact of these leaks (instead of the usual 100 years), then converting from coal to natural gas increases emissions (Lattanzio, 2015; Zhang et al., 2020). The horizon plays a role because methane concentration progressively decreases after its emission, so its warming impact is 2.5 times stronger on a horizon of 20 years than the usual horizon of 100 years. In any case, adopting a combination of renewable energy plants would mitigate emissions more efficiently (NREL, 2014). For example, wind and solar photovoltaic have a global emissions of 11 and 50 gCO<sub>2</sub>e/KWh compared with 540 gCO<sub>2</sub>e/KWh for natural gas even using GWP at 100 years.

From 2011 to 2019, Canadian national emissions increased by 4.5% according to ECCC (with LULUCF). These emissions are higher than the annual quotas allocated by three different models simulating the 2°C scenario. According to the MCJ model, this country has exhausted its entire GHG budget for the 21<sup>st</sup> century. According to the TISS-DSF model, Canada will exceed its entire *Carbon Budget* (CB) by the end of 2021. Finally, according to one scenario of the G&M model, 47% of its CB has been spent, but annual Canadian emissions are higher than annual targets every year from 2014 to 2020.

According to the ECCC, this national emission increase is attributed to higher fuel consumption for transportation, winter heating and oil and gas extraction (ECCC, 2020b). The rise in emissions for winter heating is mostly due to an increase in floor space and population. The increase in transportation emissions is caused by a steady upsurge in the number and size of vehicles. Indeed, the total number of vehicles registered increased every year from 2010 to 2019 with a 20.4% increase over that period (Statistics Canada, 2020b). Although the sales of new passenger cars decreased by 32.5%, the sale of light trucks (minivans, sport-utility vehicles, light trucks and vans) increased by 69.2% and the number of heavy trucks by 89.3% over that period (Statistics Canada, 2021). The result is that in 2017 Canada had the highest emissions level per kilometer traveled in the world according to the IEA (IEA, 2019).

Several measures could be taken to mitigate emissions from transportation. The European Commission proposed banning the sale of internal combustion engines as soon as 2025. The

deadline discussed in Canada is 2035 in the province of Quebec and 2040 in BC (CBC News, 2020; The Canadian Press, 2018). In Europe, a CO<sub>2</sub>-based sales tax on vehicles has played a role in decreasing GHG emissions in transportation (Dineen et al., 2018). There are also proposals to ban publicity for large vehicles, promote carpooling, invest more in public transportation and facilitate active modes of transportation (Boyle et al., 2020; Simpkins, 2017; Stanley et al., 2011). The federal government has created a carbon tax applied to national emissions. Prior studies have shown that such a tax could decrease transportation emissions only if it is high enough (Andersson, 2019; Pretis, 2019). This tax started at \$20 CAD per tonne in 2019 and will rise \$10 per tonne each year until reaching \$50 per tonne in 2022, then it will increase by \$15 each year until reaching \$170 per tonne in 2030 (ECCC, 2016).

Several measures could also be taken to mitigate emissions linked to winter heating and electricity consumption. In 2018, natural gas was used in 47.2% of residential heating systems (Natural Resources Canada, 2020b). Regarding commercial and institutional buildings, 43.8% of their energy use comes from natural gas (NRTEE, 2009). Building renewable energy power plants would make it possible for citizens and industries to adopt electricity as their heating source. Other proposals consist in individual initiatives. In the commercial sector, one study shows that the greatest GHG reduction could be achieved by installing heat pumps, efficient boilers, efficient lighting and high-isolation in building envelopes (Subramanyam et al., 2017a). For the residential sector, another study shows that the most GHG mitigation can be obtained with efficient lighting, efficient furnaces and high efficiency appliances (Subramanyam et al., 2017b).

Strauch proposed that there can be a positive feedback loop between policy and market for wind energy, *photovoltaic* (PV) solar panels and lithium-ion battery electric vehicles (Strauch, 2020). The drop in prices for producing these products makes it easier to adopt new policies which then favour an increased scale production and cost reduction. In order to mitigate national emissions, Canada should contribute to this positive feedback by supporting these three technologies while decreasing subsidies for fossil fuels. Alberta has programs to help its workers affected by the coal phase out (Alberta Government, 2021). Similar programs to help all fossil fuel workers transition towards a low-carbon economy can be implemented at an affordable cost for workers' benefit but also to accelerate this transition (Evans and Phelan, 2016; Louie and Pearce, 2016).



As shown above, if Canadian RURR of fossil fuels were extracted and burned, it would release 682 *gigatonnes of CO<sub>2</sub>-equivalent* (GtCO<sub>2e</sub>). A very conservative evaluation using only downstream emissions equals 533 GtCO<sub>2e</sub>. Both amounts represent more GHG than the upper limit of 420 GtCO<sub>2e</sub>, which is the *Global Carbon Budget* (GCB) providing a 67% chance to limit warming to 1.5 °C in 2100 according to IPCC (Rogelj et al., 2018). Both amounts are about half of the upper limit of 1,170 GtCO<sub>2e</sub>, which would provide a 67% chance to limit warming to 2.0 °C by 2100. These numbers confirm that most of the RURR should not be exploited.

GHG emissions linked to Canadian fossil fuel exploitation increased by 32% from 2011 to 2019. The drop of 4.9% that occurred in 2020 can be attributed to the world wide lockdowns caused by the COVID-19 pandemic. Global emissions of the Canadian fossil fuel industry represent more than twice the national emissions. In 2019, the ratio of the global LCA emissions from the Canadian fossil fuel industry of 1.566 GtCO<sub>2e</sub> over national emissions of 0.730 GtCO<sub>2e</sub> (ECCC excluding LULUCF) equals 2.15. This means that Canadian exported fossil fuels generate more than twice as much GHG as emissions within Canada. It implies that an increase of 1% of Canadian fossil fuel industry emissions at the global level cancels out a drop of 2.15% of emissions at the national level. This finding emphasizes the importance of studying both national and global emissions of fossil fuel producing countries. It also highlights a known weakness of the Paris Agreement, that is, the fact that a country can respect the agreement by reducing its emissions but increase its exports of fossil fuels to countries breaching the agreement (Lee, 2017). This weakness is described in the following way by Moss: “the accounting rules of the United Nations, under the Paris Agreement, currently allow exporters to pass on responsibility for fossil fuel emissions. We must move from this territorial model of responsibility to one that considers the whole chain of responsibility for climate harms” (Moss, 2020). There is a growing gap between the total amount of fossil fuels that producing countries are planning to extract versus the total amount needed to reach the objectives of the Paris Agreement (UN Environment Programme, 2019). So far, the accord has failed to control emissions, as was predicted from the start because of the lack of accountability and of appropriate national carbon budgets (Kemp, 2018; Rogelj et al., 2016; Spash, 2016).

Canadian fossil fuel production is influenced by political, legal, technological, economic and environmental variables. The results presented here from multiple perspectives show that Canadian emissions linked to the exploitation of fossil fuels have continued to increase (except in

2020 because of the COVID-19 pandemic) and that this country is not reducing its anthropogenic national emissions fast enough to respect the 2°C scenario. This is consistent with other studies that have observed fossil fuel production increasing and becoming a greater threat to our planetary health (Jackson et al., 2019; UN Environment Programme, 2019). Future production is difficult to anticipate, but the results presented here stress the importance of closely monitoring and of mitigating Canadian national emissions. To reach this goal it is imperative to implement international policies to limit exports of fossil fuels and to implement several national policies with an emphasis on decreasing the number of vehicles, especially larger ones, and supporting the windmill/ PV solar/ electric vehicle trio as well as supporting the transition of fossil fuel workers to the renewable sector.

## **Declaration of competing interest**

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## **Data Availability**

All data and computations are available in [this spreadsheet](#) partitioned into six tabs: Overall, Coal, Coal2, Oil, Gas and National.

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